TESTING OF HIGH WATER CONTENT COHESIVE SOILS USING THIN-WALLED TEST CELLS

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THESIS

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ABSTRACT

The concepts associated with the field of soils mechanics are now being applied to marine sediments. Because of the more complex nature of the mixture of fine mineral particles and sea water, some of these concepts do not always appear overly applicable. This is particularly true with regard to the deep sea clays. In view of their often very high water contents, a liquid behavior might well be assumed for many marine clays. The analytical methods of fluid mechanics do not satisfactorily explain the low strengths that are found in these soils. Thin-walled test cylinders were devised to allow testing of cohesive soils at high water contents. Over 50 tests were made of a test sediment, the majority above the liquid limit, to study the relationship of plasticity to water content. The results show that the gradation from liquid to plastic behavior encompasses a much wider range of water contents then previously considered.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

A. GENERAL

The requirements for accurate estimates of strength of marine sediments are numerous and are increasing. The methods used to make these estimates have not always fully satisfied the requirements. Differences between in-situ and predicted strength characteristics have been at least partially attributed to sample collection techniques. As a result, much effort has been devoted to both improving sampling equipment and perfecting in-situ testing methods. The former approach has had little direct result and the latter has proved costly, and at present, impractical.

A third approach, that of correcting laboratory data for in-situ conditions, requires a good understanding of the nature of these marine clays and the basic reason for their strength characteristics. The in-situ strength of a sediment is a complex function of the physical properties, both on a mass scale, and relative to each individual particle. If the particles were the same size, shape, orientation, and chemical composition, the problem would be far simpler.

The marine clays, the most complex of bottom sediment types, are among the most important, in that the majority of both near-shore and ocean basin floor is composed of clays. The nature of these clays is varied, ranging from fine mineral particles of predominantly terrestrial origin, to oozes composed mainly of the remains of oceanic flora and fauna. Three similar properties exist, though, in marine clay types,

which allow generalization of strength characteristics. They are all fine particles, have high water contents, and exhibit cohesive strength. The test methods most commonly utilized in dealing with these clays are those developed in terrestrial soil mechanics. The differences which exist between marine soils and terrestrial soils is a factor of their different environments, with the major difference being their higher water contents.

The strength of a soil body is a property of the physical state of the soil. Soils can be considered to be in one of four states; solid, semi-solid, plastic, or liquid. The state of the body determines which theories of mechanical behavior are applicable. The physical state of a soil body is, to a large extent, a function of the water content. To determine the state, and therefore the applicable theories, the Atterburg limits are used. Figure 1 shows these limits, as delineations between the various states, and their relationship to water content and volume.

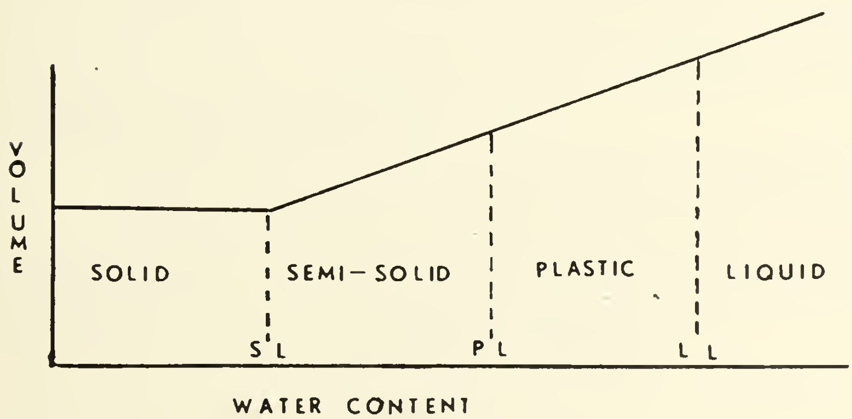

FIGURE 1. RELATIONSHIP OF PHYSICAL STATE AND WATER CONTENT.

The liquid limit (LL) is defined as the water content at which a soil passes from the plastic state to the liquid state. The plastic limit (PL) defines passage between semi-solid and plastic states, and the lesser used shrinkage limit (SL) marks the change from solid to semi-solid (Atterburg, 1905). The methods used to determine these limits are empirical, but usually fairly reproducible. Some question arises in these definitions with reference to marine clays as to the validity of the various regions, primarily in regard to the transition from plastic to liquid region.

B. FAILURE OF SOILS UNDER LOADING

The mechanism of failure of a soil column undergoing testing is ascribed to slippage along a plane, considered as the plane of failure. The resistance to slippage along this plane is termed shear strength. This resistance is caused by two separate mechanisms, internal friction, and cohesion. Internal friction is that strength given by contact of individual particles. Cohesion is a more complex quantity, and will be discussed in the succeeding section.

The first relationships developed to understand the meaning of shear strength were devised by Coulumb (1776), in his early studies of retaining walls. His equation states:

$$S = C + P \tan \phi$$

where

S = shear strength

C = cohesion,

P = normal force per unit area, and

ϕ = angle of internal friction

From the above, the resistance to slippage along a plane is equal to the cohesive strength plus the component of the normal force parallel to the plane. Coulumb assumed cohesion and angle of internal friction to be constant for a given material. The studies of Terzaghi and Hvorslev (Hvorslev, 1937), however, demonstrated that these assumptions were not valid. Their work resulted in the Terzaghi-Hvorslev failure criterion:

$$S = C' + P' \tan \phi'$$

where C', P', and ϕ' denote effective values of the parameters.

The effective normal stress (P') was found by Hvorslev to equal normal stress minus the pressure of the pore water:

$$P' = P - U_o$$

where U_o = pore pressure.

The effective values of C and ϕ account for variations of these parameters with water content, orientation, and pore pressure. Hvorslev's experiments on natural clays during the period 1934-1937 (Hvorslev, 1937) illustrated the applicability of these parameters.

When applying the Terizaghi-Hvorslev criterion to fine grained marine sediments, the assumption is usually made that ϕ' approaches zero. The reasoning for this assumption is that the increased water content tends to separate the particles so as to prevent contact or friction development. The tangent of $0^o = 0$, and the equation simplifies to:

$$S = C'$$

This indicates that all shear resistance in soils of high water content is attributable to cohesion.

The mechanism for determining shear stress resulting from an applied normal stress is attributed to Mohr (1914). The Mohr circle is used to determine the interrelationship of normal and shear stress. This mechanism is dependent on plastic behavior of the soil mass. In terms of vertical and horizontal stresses on the body, shear is evaluated as:

$$S_{13} = \frac{P_1 - P_3}{2}$$

where S_{13} = shear stress on the plane inclined 45° to the planes of P_1 and P_3

P_1 = normal stress on the horizontal plane

P_3 = normal stress on any vertical plane

The factor, K_O, relates these stresses for soils, where:

$$K_O = P_3'/P_1'$$

where

K_O = the coefficient of the earth mass at rest,

and the primes indicate effective values of P_1 and P_3. That is, for a given soil, in-situ, a normal stress on the surface will result in a lateral stress which is K_O times the normal stress. Using the Mohr circle criteria, the shear induced within the soil will have a maximum value of:

$$S_{max} = P_1 \ (1-K_O)/2$$

It has previously been assumed (Noorany and Seed, 1965) that for most cohesive soils, K_O is equal to 0.5. An objective of the present investigation was to determine if K_O remains constant for the various states of the sediments behavior.

C. SIGNIFICANCE OF COHESION

Most marine clays exhibit a resistance to shear which is, in part, independent of the normal load. This shear component is termed cohesion. The value of cohesion depends strongly on water content and the constituent minerals, and to a lesser degree on particle size. The dependence of the latter factor is demonstrated in that while the vast majority of cohesive soils are fine grained, not all fine grained soils are cohesive (Karol, 1960).

The constituents of marine soils are considered chiefly as complex silicates with some absorbed ions. Their chemical nature is such that a negative charge exists on the particle surfaces. In view of the polar nature of the water molecule, the hydrogen poles of the molecules are attracted to this negative charge. The water molecules attracted to the individual particles can be considered bound to the particle, but they also are attracted by other water molecules. If two adjacent soil particles are close enough, the bound particles of one particle are attracted by the bound water molecules of the adjacent particle, and thus the particles tend to remain stationary relative to each other. This attraction of bound water molecules is a molecular attraction, and is inversely

proportional to the distance between molecules squared. This molecular attraction can be seen as the force which opposes dislocation within the soil, independent of surface friction between soil particles. As it is a function of the distance between particles, those factors which vary distance will also cause variations of cohesion. Water content, therefore, is an important factor, as is particle orientation. The distance is also effected by particle size and shape. These last two factors also effect the value of cohesive strength in that they determine the amount of surface area exposed, and therefore the amount of attraction between the particles and the water.

The nature of cohesion as summarized above accounts for several of the properties noted for cohesive soils. The phenomenon of the sensitivity, or ratio of undisturbed strength to strength after some degree of reworking, can be explained in terms of particle orientation. In that the degree of cohesion is related to the distance between particles squared, those orientations that result in the lowest values of root mean square spacing have the highest cohesive strength. As most marine clay deposits are evolved by flocculation and subsequent settling of suspended particles, the shape of the particles serves to dictate orientation. Most clay particles are either disc or needle shaped. The disc shape particles upon settling will normally be oriented with the larger dimensional planes horizontal. This orientation results in the lowest root mean square spacing. Reworking will tend to produce random orientation and thereby lower the cohesive strength. In the case of needle shaped

particles, the settling process produces some particle interlocking, which while not of the same nature, also gives an added apparent strength. The reworking process in this case decreases this interlocking tendency and therefore also decreases the apparent cohesive strength.

The property of plasticity is also related to the nature of cohesive strength. Plasticity, or the ability to undergo large strains without rupture, is a property of only cohesive soils. If all strength was due to internal friction, then forces sufficient to cause slippage would be sufficient to cause failure. If, however, the forces are sufficient only to cause some displacement within the mass, the bonding forces attributed to cohesion continue to give some strength. This strength will continue to prevent rupture until displacement has increased to the point where the root mean squared spacing is such that cohesive strength can no longer resist the imposed force.

D. BASIC EXPERIMENTAL APPROACH

As a result of the low strengths of the marine soils above the liquid limit, the most common testing procedure in use is the vane shear test (Minhugh, 1970). This test is conducted by submerging a multi-blade vane into the test sample and applying a measured torque. This technique determines only apparent cohesive strength of the soil, and makes no determination of the relationship of the normal and shear stresses. This relationship is important because under normal loading conditions, the load is applied so as to create a normal stress, but failure occurs as a result of induced shear stress.

Another method used to determine shear strength is the "direct shear" test. This test measures shear strength on a predetermined plane under various normal loads. The major difficulty with this test is that it assumes that no preferred failure plane exists, and is an assumption perhaps false for most marine sediments. A second drawback is that the sample is frequently disturbed in the testing procedure, and any strength due to particle orientation is altered.

Two other tests have been widely used for determining strength of clays, the tri-axial and the unconfined compression tests. These are considered most applicable in the plastic region of soil behavior (Bishop and Henkel, 1962). Both are considered indirect methods of determining shear strength; that is, the strength is determined by measuring the normal stresses and applying the results to established relationships. These procedures present two difficulties with regards to testing marine soils. First, their results depend on the use of the relationships developed from the theory of plasticity, and are hence valid only for plastic soils. Secondly, testing of weak, high water content marine soils is physically extremely difficult. Many marine soils in their natural state are too weak to be tested by these methods.

In an attempt to analyze the internal stress relationship of high water content marine soils, thin-walled aluminum test cells were designed for use with the NPGS Unconfined Compression testing machine (Westfahl, 1970). The walls of the test cells allowed testing at water contents well above the liquid limit. The results of such tests

must be evaluated with regard to present understanding of mechanical behavior and the results of increased water content on the strength of clays.

The test cells developed for this study consisted of thin-walled aluminum cylinders. The response of such cylinders to internal pressures is well known. By determining their response to loadings, the internal pressure can be evaluated.

Given a cylinder of radius R, height H, and wall thickness t, it is possible to determine the response of the cylinder to an internal pressure p, by considering an incremental section of the cylinder, dH by t by Rdθ, as shown in Figure 2.

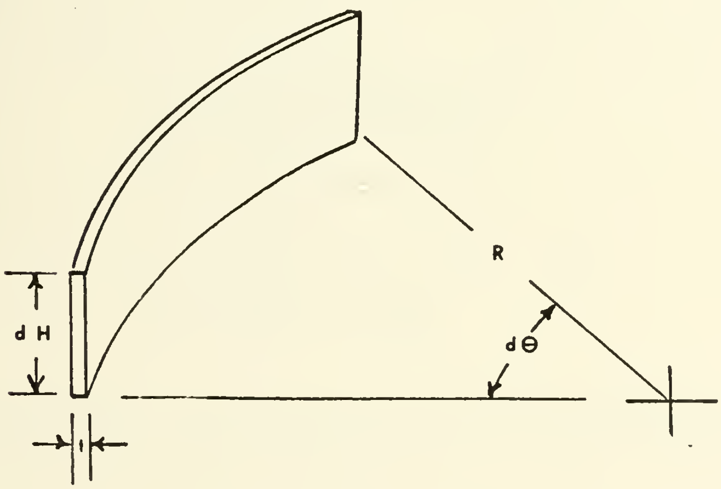

FIGURE 2. INCREMENTAL SECTION OF TEST CELL

The pressure acts normal to the surface and produces a net force in the R direction of p x Rdθ x dH. The cylinder responds to this pressure with an equal and opposite force of 2 x t x dH x sin $\frac{d\theta}{2}$ x P_t where $\frac{d\theta}{2}$ is the angle of application and P_t is the tensile stress acting tangentially in the cylinder. If the pressure acts inside the cylinder over

a height of H_1 while the total can height is H_2, then the results of integration can be shown to be:

$$P_t = (p \times R \times H_1) / (t \times H_2)$$

The distribution of stresses within the walls of the cylinder are also well known relationships. The ratios of circumferences and height to wall thickness allow the assumption of a two dimensional stress-strain distribution. The circumferential change in length per unit length, or tangential strain, s_t, is related to the tangential and longitudinal stresses by the equation: (Stippes et al, 1961)

$$s_t = \frac{1}{E} (P_t - \mu P_L)$$

where

E = Young's Modulous,

P_t = tangential stress,

P_L = longitudinal stress, and

μ = Poison's Ratio

The analysis of the stress-strain relationship may be simplified by allowing the ends of the cylinder to move unrestrained, thereby supporting no longitudinal stress. With P_L equaling zero, and multiplying through by E, the equation, solved for P_t becomes:

$$P_t = E \times s_t$$

Substituting this equation into the previously determined equation for tangential stress, and solving for internal pressure, p, it can be seen that

$$p = (s_t \times E \times t \times H_2) / (R \times H_1)$$

Young's Modulous, E, is a constant for a given metal, and t, R, H_2, and H_1 are easily measured parameters. It is seen then that by determining the tangential strain, the internal pressure can be evaluated.

II. TEST EQUIPMENT

A. NPGS UNCONFINED COMPRESSION TESTING MACHINE

The vertical stresses on the test samples were imposed, controlled, and recorded using the unconfined compression testing machine designed and assembled by Westfahl (1970). Figure 3 shows the assembled machine, with the aluminum test cell designed for this investigation installed.

The major components of the test machine, in addition to the structural members, are the machine screw jactuator, variable speed motor, the motor speed control, and the force transducer. These are shown in Figures 4 and 5. The force on the test cell was imposed by driving the machine screw jactuator at low speed. The force was measured by Daytronics Corporation equipment, the force transducer being a model 52-50-A, with power supplied by a Model 300 D Transducer amplifier-indicator. The force signals from the transducer were conditioned and amplified by a module in the amplifier-indicator. The conditioned output from the module was used as a variable input to an X-T recorder.

B. TEST CELL EQUIPMENT

The lateral pressures in the soil sample were monitored utilizing thin-walled cylinders and strain gage equipment. The cylinders were machined from 2025 aluminum. Of the various metals available,

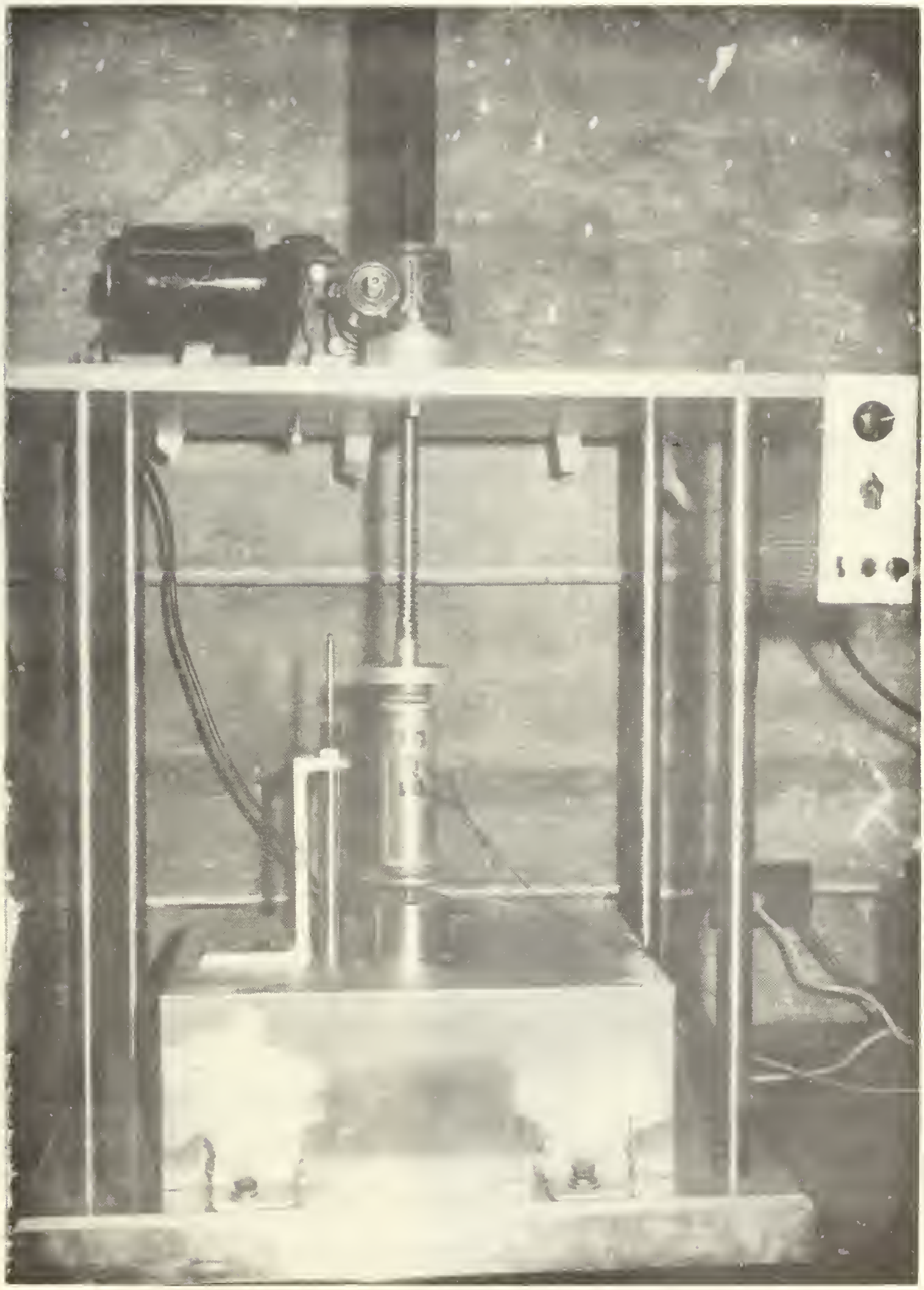

FIGURE 3. NPGS UNCONFINED COMPRESSION TESTING MACHINE WITH ALUMINUM TEST CELL.

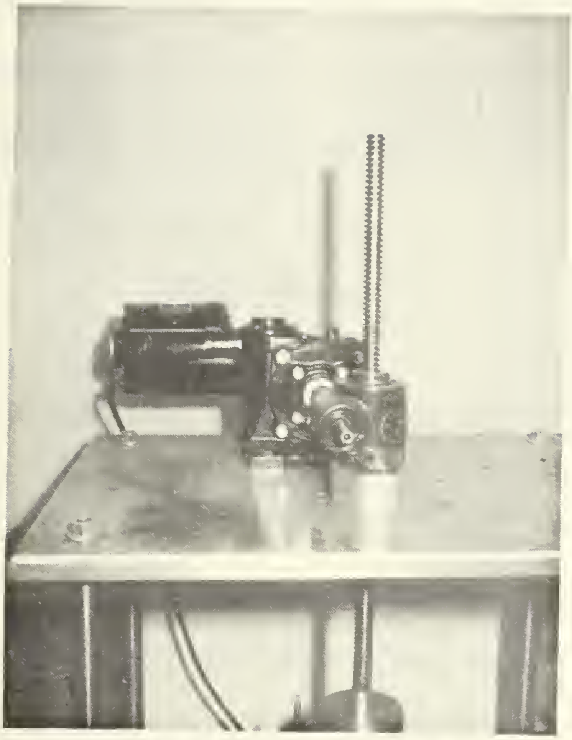

FIGURE 4.

ELECTRIC MOTOR AND MACHINE SCREW JACTUATOR FOR UNCONFINED COMPRESSION TESTING MACHINE.

FIGURE 5.

ELECTRIC MOTOR CONTROLLER AND FORCE TRANSDUCER USED IN INVESTIGATION.

aluminum gave the best ratio of tangential strain to internal pressure. Open ended cylinders were used to simplify loading and to negate the influence of longitudinal stress. The cells used in the tests had the following dimensions:

Inside Radius	=	0.937 inches
Height	=	5.00 inches
Thickness	=	0.020 inches

End plugs were constructed for the cylinders using the same metal stock. The radius of the plugs was such as to allow minimum clearance between the plugs and the cell wall while allowing vertical movement of the plugs within the cells. Under loading conditions, the free movement prevented friction, which would have induced longitudinal stress within the cell walls. The minimum clearance was to make the cylinder watertight. However, this proved impossible if free movement was to be insured. Therefore, round cork gaskets were made to fit between the end plugs and the sample. Lubricating the end plugs and gaskets with a petroleum jelly served to ensure both watertight seals, and free movement. A photograph of the test cells, end plugs and gaskets is included as Figure 6.

Tangential strain was measured by various types of SR-4 strain gages. These were foil-backed, temperature compensating gages. The variation of resistance of the strain gage due to strain was measured on a portable SR-4 type L strain gage indicator, shown in Figure 7.

FIGURE 6. TEST CELL WITH STRAIN GAGES ATTACHED. END PLUGS, CORK GASKET, AND SPACERS ARE ALSO SHOWN.

FIGURE 7. STRAIN GAGE INDICATOR USED IN INVESTIGATION.

C. AUXILIARY TEST EQUIPMENT

To allow a more meaningful interpretation of test data, several auxiliary tests were performed on the samples. Water content determinations were made using an analytic balance accurate to within 0.01 gm, and a drying oven thermostatically controlled at 110 ± 5 °C. Liquid limit tests were conducted using a mechanical liquid limit device and then conducting water content determinations in the standard manner. Periodic Bulk Wet Density determinations were made using the known volume of the test cells, and the balance described above. The balance was further used, in conjunction with an air comparison pycnometer, accurate to within 0.01 cc, for specific gravity of solids determination. Measurements of cylinder radius, thickness, and height, and sample height were made using calipers accurate to within 0.001 inches.

III. TEST PROCEDURE

The tests in this investigation were conducted on samples of clay from Seal Beach Lagoon, California. Previous tests on these samples had been conducted by King (1969). These samples had been stored since collection in an emersed condition. No drying had occurred, and the only deterioration apparent was in the form of rust from the storage containers. Water content of the stored clay was measured at 70%. To insure that results were representative of the general mass, and not a single sample, 14 samples were used during this investigation.

It was realized that it would not be possible to find a homogeneous soil body exhibiting the wide range of water contents desired for testing. As a consequence, it was decided to use remolded samples, and to vary the water content by allowing a fairly uniform and slow drying between test runs. The samples were remolded during the drying periods and this served to ensure satisfactorily uniform drying. Sufficient material was utilized for each sample to allow multiple tests on the sample even with some of the sample used after each test for water content measurement. Bulk Wet Density determinations were made periodically to ensure that all tests were conducted on fully saturated samples. Liquid limit tests were made on every other sample, and the dried samples from these tests were used for specific gravity determinations. This testing was done primarily to insure homogeneity. The liquid limit was evaluated as $55.0 \pm 0.5\%$.

Each sample was removed from the storage container, and the container was then resealed to prevent drying. A portion of the removed sample was tested for water content, and the remainder of the sample was remolded in a large dish. The sample was then transferred to the test cell using a spatula, and again reworked to minimize the possibility of entrapped air. This was done by use of a column of 1/4-inch spacers inside the cylinder. One of the cork gaskets was placed on top of the spacers, and the cylinder was filled from the gasket to the top. Several spacers were removed and then more sample was added. This was continued until approximately 4 inches of sample was contained within the cylinder. The open end of the cylinder was then capped using a second gasket and an end plug. A slight pressure was exerted on the end plug to force the sample toward the end without a plug. The second end plug was then added. Slight pressure was then exerted for two reasons; first, to center the sample, and second, to ensure that both end plugs moved without friction within the cylinder walls. Figure 8 is a cross sectional drawing of the completed assembly ready for testing. The filled test cell was then installed in the unconfined compression machine as shown in Figure 9. Spacers were placed between the end plugs and lower platens to ensure free movement of the cylinder longitudinally. The upper platen was lowered so that the test cell was held in place, and the strain gages were connected to the strain gage indicator. The indicator was nulled and the force transducer and chart recorder were

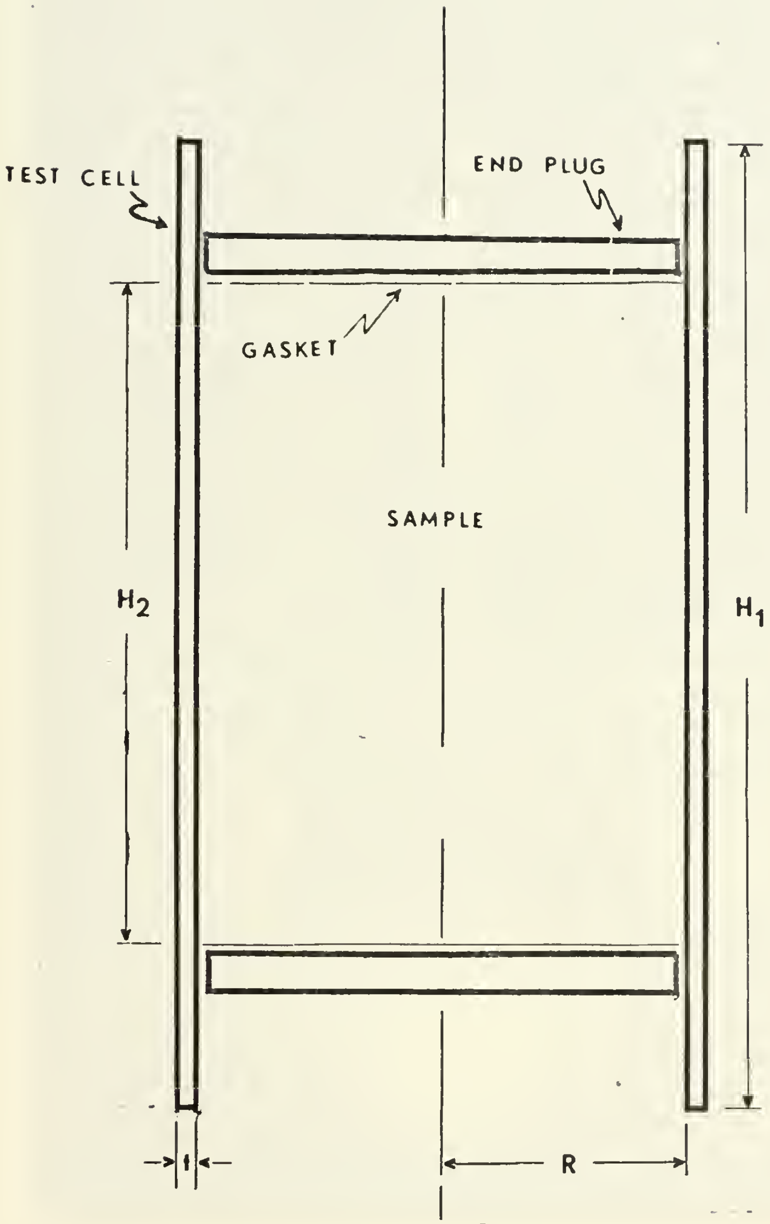

FIGURE 8. TEST CELL CROSS SECTION.

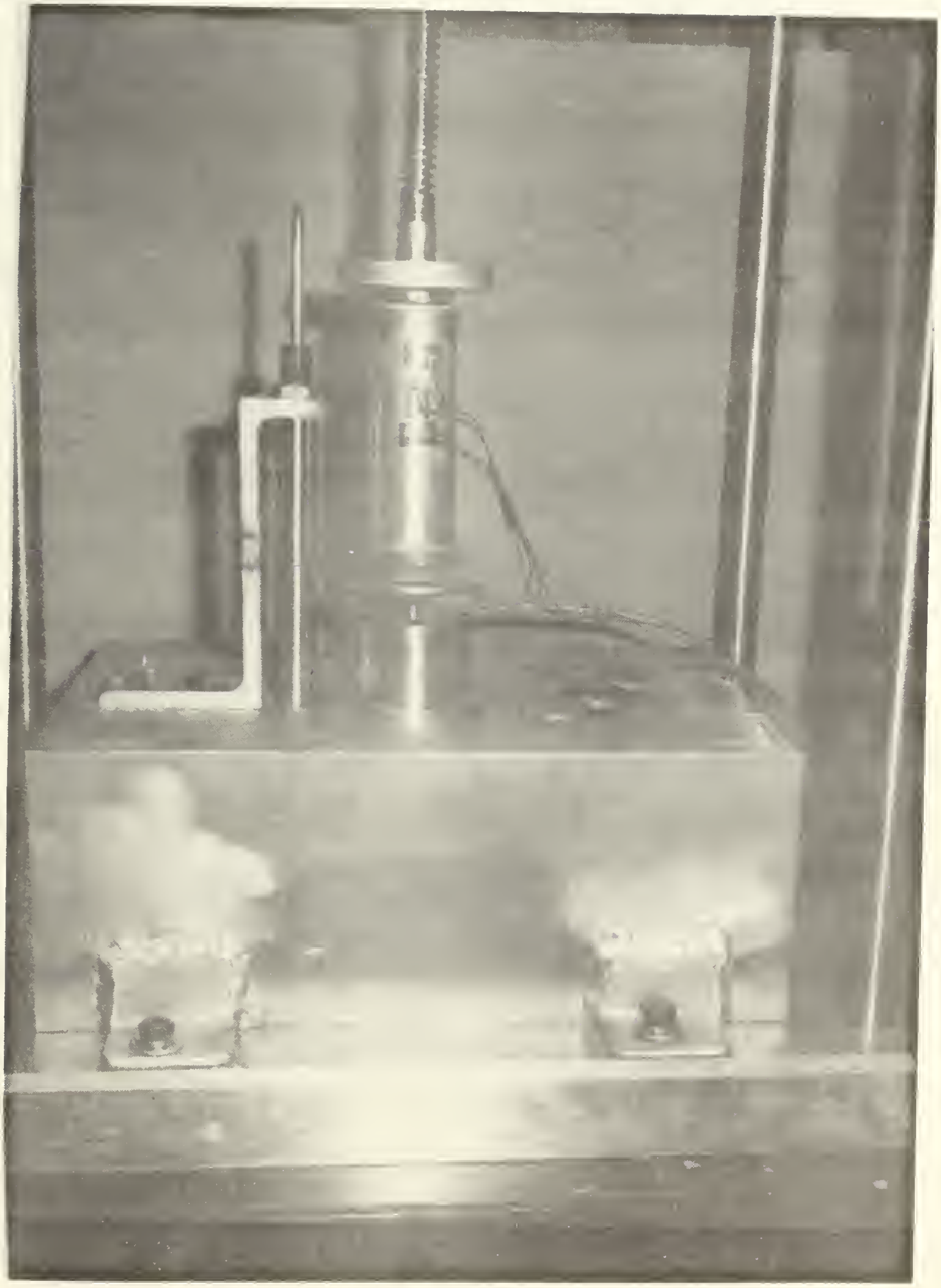

FIGURE 9. TEST CELL READY FOR TESTING.

zeroed. The distance between the upper and lower platens was measured and from this, sample height was calculated and recorded.

The motor for the machine screw jactuator was operated at a speed sufficiently slow to allow the operator to monitor the tangential strain. For most sample runs, a rate of less than 1% longitudinal strain per minute was used. Rates of up to 10% per minute were tried, with no apparent effect on the results. However, the slower rate proved more convenient for the test operations. The maximum load applied during the tests was in the range of 75 to 85 pounds. This insured that maximum longitudinal strain on the sample was less than 2%, necessary to insure that stress relationships as determined were essentially independent of sample distortion.

The variables of interest were the normal force and the tangential strain. The method used to record these variables proved satisfactory. The strain gage indicator available had no output capability, so manual recording of strain was necessary. The output of the force transducer amplifier-indicator was used as the variable input to the X-T recorder. The force versus time plot thus obtained was modified to include indications of strain increments. Increments of 10 micro-inches per inch of strain were indicated on the output force-time plots by alternately lifting and lowering the recorder pen. Figure 10 is a sample of one of the graphs thus obtained. Point O indicates zero conditions at start of test. Point A indicates 10 micro-inches per inch strain. Point B indicates pen lowered to signal 20 micro-inches. The break in the

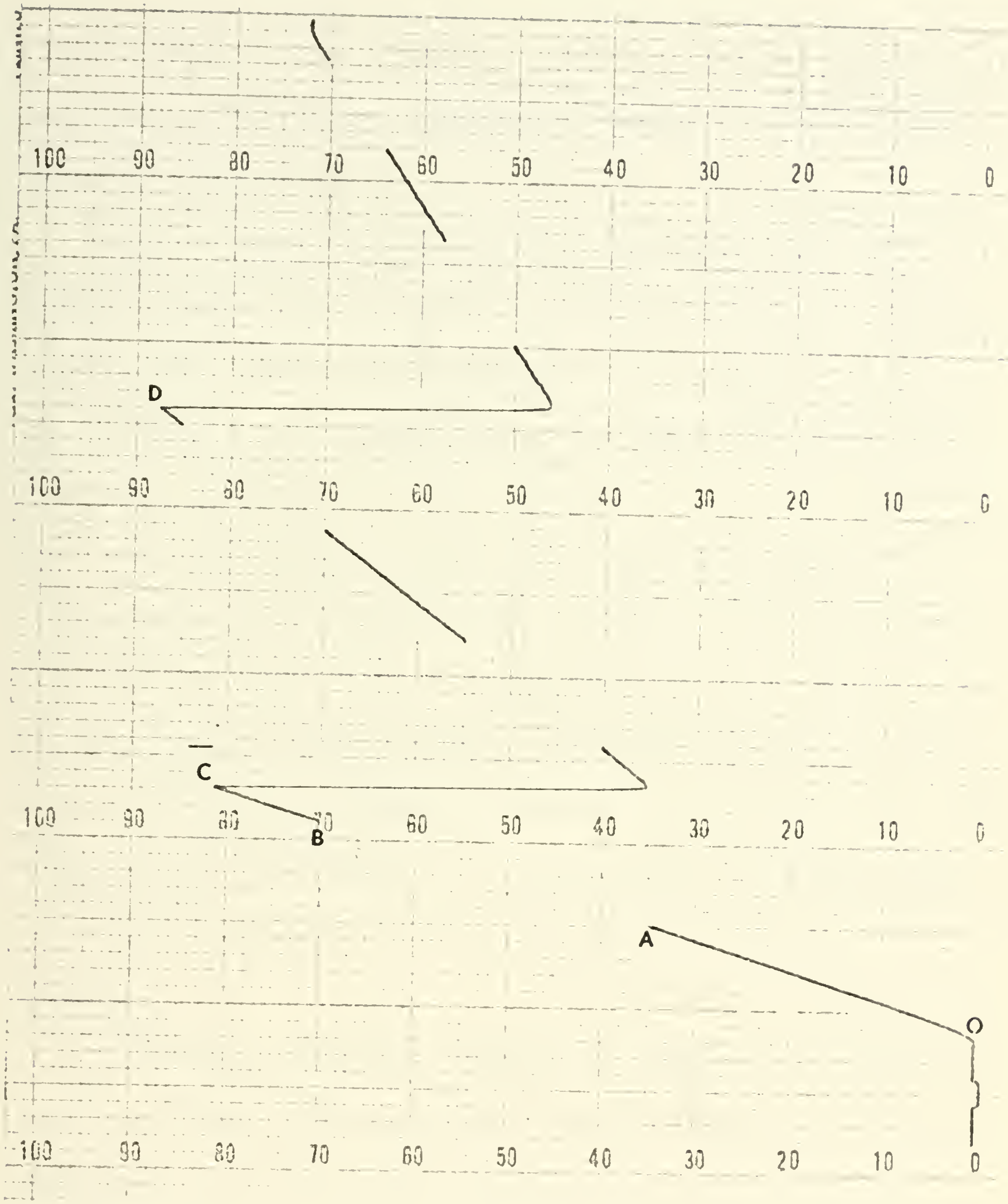

FIGURE 10. FORCE VERSUS TIME OUTPUT PLOT, MODULATED TO INDICATE INCREMENTS OF STRAIN.

curve at Point C marks a change of scale from 0.2 lbs force per scale unit to 5 lbs per unit, and Point D represents a further scale change to 10 lbs per unit.

After the maximum force for each run was reached, the screw drive was stopped, and total change of sample height was measured. All tests were conducted so that sample change of height was less than 2%. The force was then removed, the strain gages disconnected, and the sample extruded from the cell. The sample was placed in a drying dish, and a small portion was taken for a water content determination. A new sample was then placed within the test cell, and the previously tested sample allowed to dry. As stated previously, the samples were reworked during the drying process. Approximately 4 tests were made on each sample, with differences of at least 2% in water content in each subsequent run. The samples were discarded when it became apparent either that drying was not uniform or that the sample was no longer fully saturated.

In the early stages of the testing, the assumption was made that below the liquid limit, the coefficient of Earth pressure at rest, K_O, would be 0.5, so samples were discarded when their water contents approached the liquid limit. However, during preliminary data reduction, it became apparent that this was not the case. Subsequent samples were therefore allowed to dry as far below this limit as possible. Three samples dried to water contents of about 45% before becoming unsaturated.

IV. ANALYSIS OF DATA

The output plots were reduced to a tabular notation of tangential strain versus force. While the graphs of these functions were proportional to the desired P_1 versus P_3 curves, their dependence upon sample height limited the utility. The determinations that were desired were the relationship of the vertical stress P_1 to the horizontal stress P_3 and the relationship of this to the water content.

The pressure against the walls of the cylinder at any point equals the radial stress P_R of the soil column at that point. Remolding of the sample eliminated any inhomogeneities within the column, so P_R is considered equal to P_3.

The earlier equation:

$$p = \frac{s_t \times E \times t}{r} \quad \frac{H_2}{H_1}$$

becomes:

$$P_3 = \frac{s_t \times E \times t \times H_2}{r \times H_1}$$

Using the fact that

$$K_O = P_3/P_1$$

and recognizing that the normal stress P_1 equals the normal force F divided by the area of application, an equation which gives K_O in terms of the measured variables is:

$$K_O = C_O (s_t / (F \times H_1)$$

where

C_O = cell constant,

s_t = tangential strain,

F = normal force, and

H_1 = sample height

The values of C_O were obtained by periodic calibrations of the cylinders using water (K_O = 1) in place of the sample. Seven such calibrations were conducted and each gave a value of

$$C_O = 1.58 \pm 0.04$$

The Naval Postgraduate School IBM 360 digital computer was used for the data reduction. The required variables and constants were used as an input for a program which solved for P_1, P_3, and K_O. A table of normal force, tangential strain, P_1, P_3, and K_O for each run was obtained. Eight runs were terminated either due to system malfunction or as a result of anomalous data. The tables for the 55 successful runs are included as Appendix A.

The computer was also used to plot P_1 versus P_3 for all tests. Figure 11 illustrates one such plot, with a best fit straight line. All 55 successful runs approximated straight lines for the range of interest. The slopes of these lines were evaluated as K_O for that particular run, and K_O versus water content was plotted for the test samples. Figure 12 is the final plot of K_O versus water content.

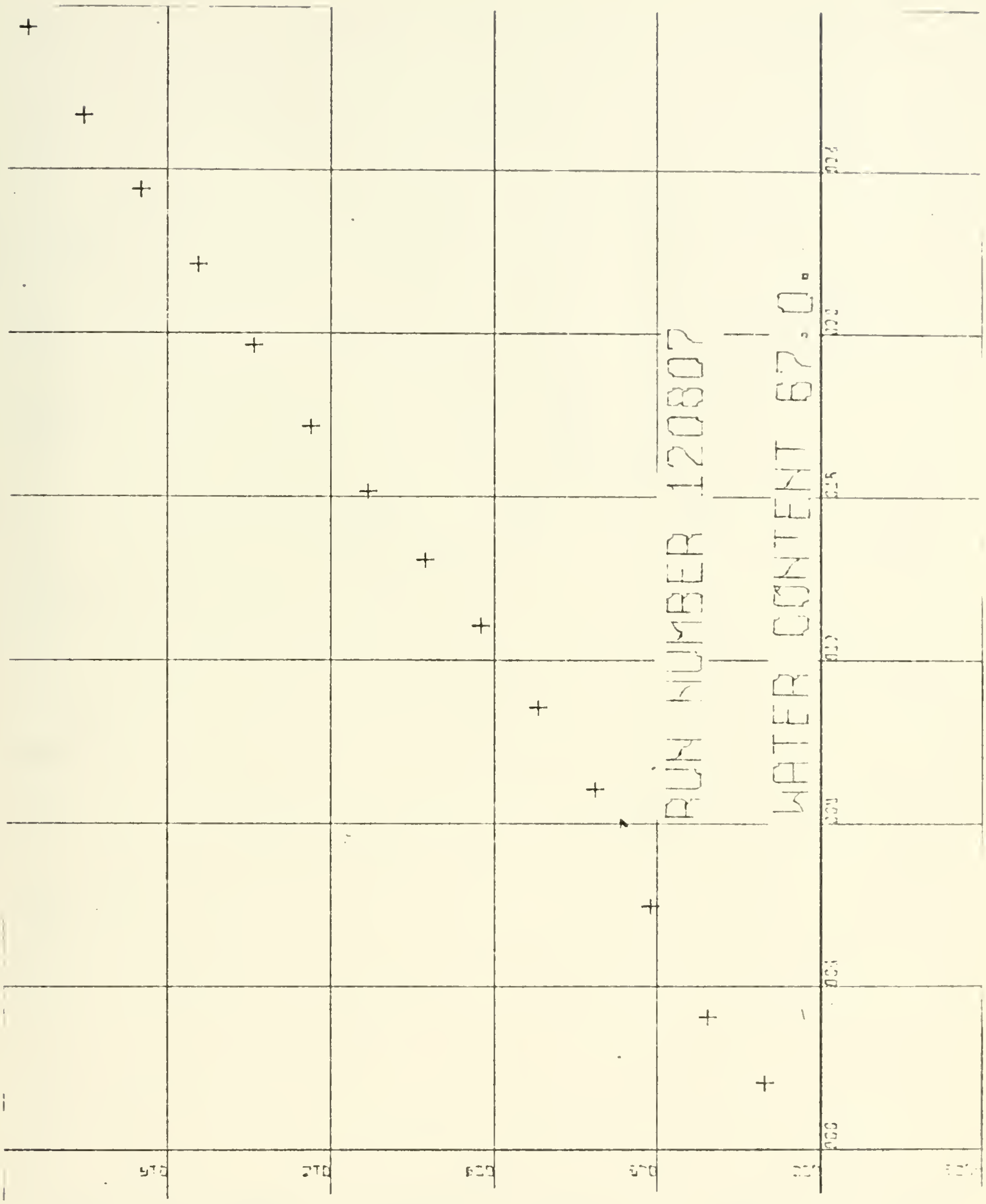

FIGURE 11. SAMPLE P_1 VERSUS P_3 GRAPH.

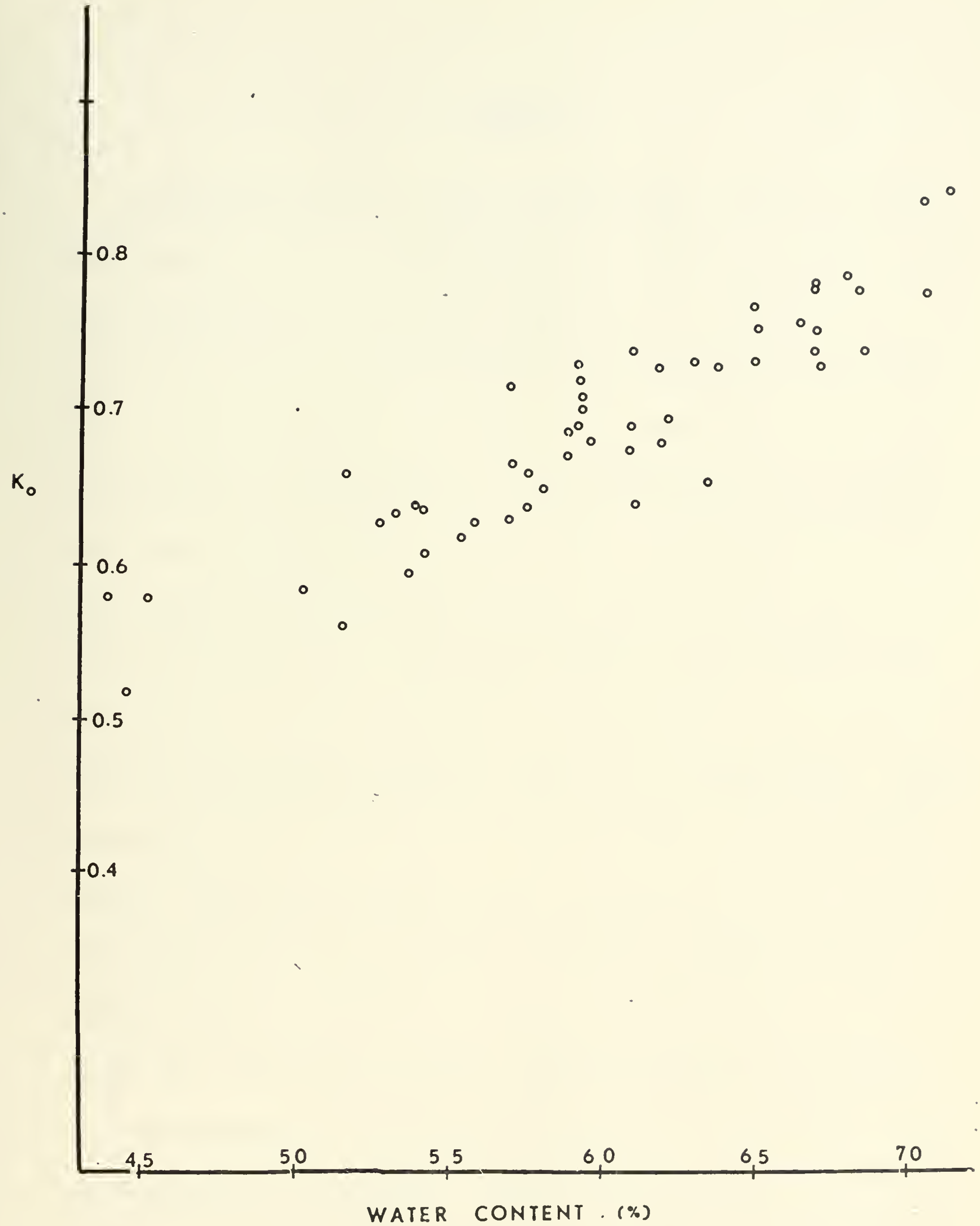

FIGURE 12. K_O VERSUS WATER CONTENT.

V. RESULTS

For the entire range of water contents tested, from 45% to 71%, there appeared a strong dependence of K_O upon the water content. The value of liquid limit as measured in seven tests on samples was 55.1%. Further, K_O for a given water content was constant throughout the full range of forces applied. The position of the strain gages on the cans was moved from mid height as far as one inch below the top of the cylinder with no apparent effect on the results. The method used in these tests to determine the tangential strain appears to be the greatest shortcoming of the procedure. The range of pressures was such that maximum strain was less than 150 micro inches per inch. The accuracy of the strain gage indicator used was rated at $\pm$ 0.5 micro inches. When considered in light of 10 micro inch intervals, this is not fully satisfactory. The initial objective of this work was to test the concept of stress measurement using confining cylinders. The relationship of normal to horizontal stress was evaluated at values well above the liquid limit. With this objective in mind the results were favorable.

The question of the exact nature of soils above the liquid limit was answered to some degree. There is a marked plasticity exhibited even above the limit, while the change from liquid to plastic behavior below the limit is not as rapid as envisioned. This bi-state behavior of clays suggests that empirical solutions to strength problems are

required, and raises questions as to the applicability of testing based purely on a plastic behavior. The triaxial and unconfined compression tests are the major examples of indirect tests, and predictions of soil strength made from the results of these tests relate to plastic theory. This does not apply to non-cohesive sediments, as plasticity is a property only of cohesive soils.

VI. CONCLUSIONS

A. K_O-WATER CONTENT RELATIONSHIP

It is apparent from the results of this work that a dependence of K_O upon water content exists, though the degree of this dependence is not completely clear. It was initially assumed that the curve of K_O versus water content would be close to asymptotic to 0.5 below the liquid limit, and to 1.0 above the limit. A wide region of bi-state behavior appears to exist, but definite boundaries of the bi-state behavior were not detected. However, some asymptotic behavior does appear to exist, as depicted in Figure 12. The behavior seen could be approximated by either an arctan curve or one quadrant of a sine curve. This latter would support Jazy's approximation of (Jazy, 1944):

$$K_O = 1 - \sin \phi'$$

where ϕ' = effective or apparent angle of friction. Since cohesion becomes more important in the shear problem, for higher water contents apparent ϕ will be some function of cohesive strength versus normal stress. The higher water contents result in greater inter-particle distance, and therefore decreases cohesive strength. This decrease is proportional to the inverse of the square of the separation distance. The increase of spacing is a factor of water content, particle size, and orientation. The indeterminate nature of these variables indicates the necessity of empirical solution to the problem.

Combining the earlier stated equation of resultant shear and the modification of the Terzaghi-Hvorslev criterion, one arrives at the solution:

$$P_{1_{max}} = S_{max} \times 2/(1 - K_O)$$

and for high water contents, since S = C,

$$P_{1_{max}} = C \times 2/(1 - K_O)$$

As would be expected, these become indeterminate as K_O approaches 1.0. However, the immediate results of these tests that show non-unity values for K_O above the liquid limit indicate applicability within the ranges of water contents of most marine clays.

B. CONFINED COMPRESSION TESTING

The test cell approach allowed an examination of the high water content clays with regard to their internal stress distribution. Standard test methods have not satisfactorily determined these relationships. Direct methods of shear determination conducted on samples of higher water content measure only cohesive strength. Indirect methods are difficult because of the low degree of plasticity. Loads in actual applications would be applied to the soils in the form of normal loads. Therefore, the resultant stresses of such loads are of interest and must be analyzed. New methods must be considered, in order to overcome the difficulties of dealing with low strength high water content marine clays. The solution may well be a test such as conducted in this study,

in conjunction with use of the vane shear to evaluate cohesive strength. This test cell approach is not dependent upon single state behavior for validity, and so can be applied in the area of interest. It has served to more completely define the problem.

VII. RECOMMENDATIONS FOR FURTHER WORK

The primary study recommended concerns the nature of the water within sediments. As a result of the test of this investigation, it is believed that some percentage of the water molecules is tightly bound to the soil particles. A complex test utilizing heavy water (D_2O) is suggested to determine if this is true. If bonding of the surface molecules is not strong enough to permanently affix the surface water, the particles would be more prone to move relative to one another and the mass would more closely approximate a water matrix with the particles floating in such a matrix. It is theorized, rather, that inter-particle attraction causes semi-permanent positioning of the soil particles.

The tests of this study were conducted on a single clay type. It is recommended that further tests be conducted on various cohesive and non-cohesive soils, and further, that testing cover the full range from natural water content as low as the plastic limit. In conducting further tests, it is recommended that different sized containers be used, and that more refined strain measurement and recording systems be employed.

APPENDIX A - TEST DATA

RUN NUMBER 120801 WATER CONTENT 70.6

FORCE	STRAIN	P1	P3	K
6.10	10.0	2.21	1.59	0.719
9.10	20.0	3.29	3.18	0.965
15.10	30.0	5.47	4.77	0.872
18.80	40.0	6.81	6.36	0.934
24.70	50.0	8.94	7.94	0.888
31.20	60.0	11.29	9.53	0.844
39.20	70.0	14.19	11.12	0.784
46.80	80.0	16.94	12.71	0.750
52.20	90.0	18.90	14.30	0.757
58.60	100.0	21.21	15.89	0.749
62.90	110.0	22.77	17.48	0.768
68.80	120.0	24.91	19.07	0.766
73.20	130.0	26.50	20.65	0.779

RUN NUMBER 120802 WATER CONTENT 70.6

FORCE	STRAIN	P1	P3	K
4.20	10.0	1.52	0.14	0.095
9.60	20.0	3.48	0.29	0.083
12.80	30.0	4.63	0.43	0.094
18.20	40.0	6.59	0.58	0.088
25.10	50.0	9.09	0.72	0.079
31.60	60.0	11.44	0.87	0.076
35.80	70.0	12.96	1.01	0.078
40.90	80.0	14.81	1.16	0.078
46.00	90.0	16.65	1.30	0.078
51.50	100.0	18.64	1.44	0.077
57.00	110.0	20.63	1.59	0.077
62.50	120.0	22.62	1.73	0.077
67.00	130.0	24.25	1.88	0.077
73.00	140.0	26.43	2.02	0.077
79.00	150.0	28.60	2.17	0.076

RUN NUMBER 120803 WATER CONTENT 68.5

FORCE	STRAIN	P1	P3	K
4.00	10.0	1.45	1.63	1.129
8.00	20.0	2.90	3.27	1.129
15.50	30.0	5.61	4.90	0.874
23.00	40.0	8.33	6.54	0.785
28.00	50.0	10.14	8.17	0.806
33.00	60.0	11.95	9.81	0.821
38.50	70.0	13.94	11.44	0.821
44.00	80.0	15.93	13.07	0.821
50.00	90.0	18.10	14.71	0.813
57.00	100.0	20.63	16.34	0.792
65.00	110.0	23.53	17.98	0.764
73.00	120.0	26.43	19.61	0.742
79.00	130.0	28.60	21.24	0.743
85.00	140.0	30.77	22.88	0.744

RUN NUMBER 120804 WATER CONTENT 68.5

FORCE	STRAIN	P1	P3	K
5.00	10.0	1.81	1.66	0.916
9.90	20.0	3.58	3.32	0.925
17.50	30.0	6.33	4.97	0.785
25.00	40.0	9.05	6.63	0.733
32.50	50.0	11.76	8.29	0.705
40.00	60.0	14.48	9.95	0.687
47.50	70.0	17.19	11.60	0.675
55.00	80.0	19.91	13.26	0.666
61.50	90.0	22.26	14.92	0.670
67.80	100.0	24.54	16.58	0.675
74.80	110.0	27.08	18.24	0.673
80.00	120.0	28.96	19.89	0.687

RUN NUMBER 120805 WATER CONTENT 67.0

FORCE	STRAIN	P1	P3	K
5.50	10.0	1.99	1.55	0.781
12.60	20.0	4.56	3.11	0.682
16.80	30.0	6.08	4.66	0.767
22.50	40.0	8.14	6.22	0.763
30.60	50.0	11.08	7.77	0.702
35.80	60.0	12.96	9.33	0.720
41.50	70.0	15.02	10.88	0.724
47.50	80.0	17.19	12.43	0.723
54.00	90.0	19.55	13.99	0.716
59.80	100.0	21.65	15.54	0.718
67.00	110.0	24.25	17.10	0.705
72.50	120.0	26.24	18.65	0.711
79.00	130.0	28.60	20.21	0.707

RUN NUMBER 120806 WATER CONTENT 67.0

FORCE	STRAIN	P1	P3	K
5.80	10.0	2.10	1.55	0.740
10.60	20.0	3.84	3.11	0.810
18.00	30.0	6.52	4.66	0.716
25.00	40.0	9.05	6.22	0.687
30.00	50.0	10.86	7.77	0.716
35.00	60.0	12.67	9.33	0.736
40.50	70.0	14.66	10.88	0.742
46.50	80.0	16.83	12.43	0.739
52.30	90.0	18.93	13.99	0.739
58.00	100.0	21.00	15.54	0.740
63.50	110.0	22.99	17.10	0.744
69.00	120.0	24.98	18.65	0.747
74.00	130.0	26.79	20.21	0.754
80.00	140.0	28.96	21.76	0.751

RUN NUMBER 120807 WATER CONTENT 67.0

FORCE	STRAIN	P1	P3	K
4.50	10.0	1.63	1.39	0.852
9.00	20.0	3.26	2.78	0.852
16.50	30.0	5.97	4.16	0.697
24.50	40.0	8.87	5.55	0.626
30.00	50.0	10.86	6.94	0.639
35.50	60.0	12.85	8.33	0.648
40.00	70.0	14.48	9.72	0.671
44.60	80.0	16.15	11.11	0.688
49.00	90.0	17.74	12.49	0.704
54.50	100.0	19.73	13.88	0.704
60.00	110.0	21.72	15.27	0.703
65.00	120.0	23.53	16.66	0.708
70.00	130.0	25.34	18.05	0.712
76.00	140.0	27.51	19.44	0.706

RUN NUMBER 120808 WATER CONTENT 65.0

FORCE	STRAIN	P1	P3	K
4.20	10.0	1.52	1.39	0.915
8.60	20.0	3.11	2.78	0.894
15.00	30.0	5.43	4.17	0.769
21.00	40.0	7.60	5.57	0.732
26.00	50.0	9.41	6.96	0.739
30.50	60.0	11.04	8.35	0.756
36.00	70.0	13.03	9.74	0.747
42.00	80.0	15.20	11.13	0.732
47.00	90.0	17.01	12.52	0.736
52.00	100.0	18.82	13.92	0.739
57.00	110.0	20.63	15.31	0.742
63.00	120.0	22.81	16.70	0.732
69.00	130.0	24.98	18.09	0.724
74.50	140.0	26.97	19.48	0.722
80.50	150.0	29.14	20.87	0.716

RUN NUMBER 120809 WATER CONTENT 65.0

FORCE	STRAIN	P1	P3	K
7.50	10.0	2.71	1.54	0.568
12.50	20.0	4.52	3.08	0.681
16.80	30.0	6.08	4.63	0.760
20.80	40.0	7.53	6.17	0.819
26.60	50.0	9.63	7.71	0.801
32.70	60.0	11.84	9.25	0.781
38.80	70.0	14.05	10.79	0.768
44.50	80.0	16.11	12.33	0.766
50.30	90.0	18.21	13.88	0.762
56.90	100.0	20.60	15.42	0.748
62.50	110.0	22.62	16.96	0.750
68.00	120.0	24.62	18.50	0.752
73.60	130.0	26.64	20.04	0.752

RUN NUMBER 120810 WATER CONTENT 65.0

FORCE	STRAIN	P1	P3	K
7.80	10.0	2.82	1.55	0.550
13.60	20.0	4.92	3.11	0.631
18.80	30.0	6.81	4.66	0.685
23.50	40.0	8.51	6.22	0.731
29.60	50.0	10.72	7.77	0.725
35.50	60.0	12.85	9.33	0.726
41.70	70.0	15.10	10.88	0.721
47.50	80.0	17.19	12.43	0.723
52.50	90.0	19.00	13.99	0.736
58.80	100.0	21.29	15.54	0.730
63.50	110.0	22.99	17.10	0.744
70.60	120.0	25.56	18.65	0.730
75.80	130.0	27.44	20.21	0.736
81.50	140.0	29.50	21.76	0.738

RUN NUMBER 120811 WATER CONTENT 65.0

FORCE	STRAIN	P1	P3	K
11.00	10.0	3.98	2.01	0.504
18.50	20.0	6.70	4.01	0.599
26.00	30.0	9.41	6.02	0.640
32.00	40.0	11.58	8.03	0.693
41.00	50.0	14.84	10.03	0.676
47.00	60.0	17.01	12.04	0.708
52.80	70.0	19.11	14.05	0.735
61.00	80.0	22.08	16.06	0.727
69.10	90.0	25.01	18.06	0.722
78.00	100.0	28.24	20.07	0.711

RUN NUMBER 120812 WATER CONTENT 63.0

FORCE	STRAIN	P1	P3	K
9.90	10.0	3.58	2.27	0.633
15.50	20.0	5.61	4.54	0.809
22.90	30.0	8.29	6.81	0.821
30.80	40.0	11.15	9.08	0.814
45.50	50.0	16.47	11.35	0.689
52.30	60.0	18.93	13.62	0.719
59.90	70.0	21.68	15.89	0.733
69.10	80.0	25.01	18.16	0.726
77.50	90.0	28.05	20.43	0.728

RUN NUMBER 120814 WATER CONTENT 59.0

FORCE	STRAIN	P1	P3	K
8.80	10.0	3.19	1.51	0.474
15.50	20.0	5.61	3.02	0.538
20.60	30.0	7.46	4.53	0.607
25.50	40.0	9.23	6.04	0.654
31.80	50.0	11.51	7.55	0.655
38.00	60.0	13.76	9.05	0.658
43.50	70.0	15.75	10.56	0.671
51.50	80.0	18.64	12.07	0.648
59.00	90.0	21.36	13.58	0.636
65.50	100.0	23.71	15.09	0.636
72.00	110.0	26.06	16.60	0.637
78.00	120.0	28.24	18.11	0.641

RUN NUMBER 120815 WATER CONTENT 59.0

FORCE	STRAIN	P1	P3	K
8.20	10.0	2.97	1.52	0.511
15.00	20.0	5.43	3.03	0.559
20.60	30.0	7.46	4.55	0.610
26.00	40.0	9.41	6.07	0.645
32.50	50.0	11.76	7.59	0.645
38.50	60.0	13.94	9.10	0.653
45.00	70.0	16.29	10.62	0.652
52.50	80.0	19.00	12.14	0.639
58.80	90.0	21.29	13.65	0.641
65.50	100.0	23.71	15.17	0.640

RUN NUMBER 120901 WATER CONTENT 54.4

FORCE	STRAIN	P1	P3	K
11.00	10.0	3.98	1.31	0.330
17.00	20.0	6.15	2.63	0.427
23.10	30.0	8.36	3.94	0.472
28.50	40.0	10.32	5.26	0.510
34.00	50.0	12.31	6.57	0.534
40.00	60.0	14.48	7.89	0.545
45.80	70.0	16.58	9.20	0.555
52.00	80.0	18.82	10.52	0.559
58.50	90.0	21.18	11.83	0.559
65.50	100.0	23.71	13.15	0.555

RUN NUMBER 120902 WATER CONTENT 54.4

FORCE	STRAIN	P1	P3	K
11.80	10.0	4.27	1.32	0.309
20.80	20.0	7.53	2.64	0.351
26.00	30.0	9.41	3.96	0.421
31.50	40.0	11.40	5.28	0.463
37.50	50.0	13.57	6.60	0.487
43.00	60.0	15.57	7.93	0.509
48.00	70.0	17.38	9.25	0.532
53.50	80.0	19.37	10.57	0.546
60.00	90.0	21.72	11.89	0.547
65.50	100.0	23.71	13.21	0.557
71.50	110.0	25.88	14.53	0.561
76.50	120.0	27.69	15.85	0.572

RUN NUMBER 120903 WATER CONTENT 53.3

FORCE	STRAIN	P1	P3	K
12.80	10.0	4.63	1.32	0.285
19.90	20.0	7.20	2.64	0.367
26.70	30.0	9.67	3.97	0.410
32.00	40.0	11.58	5.29	0.457
38.00	50.0	13.76	6.61	0.481
43.50	60.0	15.75	7.93	0.504
49.00	70.0	17.74	9.26	0.522
56.00	80.0	20.27	10.58	0.522
62.50	90.0	22.62	11.90	0.526
67.50	100.0	24.43	13.22	0.541
73.00	110.0	26.43	14.55	0.550

RUN NUMBER 120905 WATER CONTENT 50.4

FORCE	STRAIN	P1	P3	K
15.50	10.0	5.61	1.68	0.299
23.50	20.0	8.51	3.35	0.394
29.00	30.0	10.50	5.03	0.479
36.50	40.0	13.21	6.71	0.508
43.50	50.0	15.75	8.39	0.533
54.50	60.0	19.73	10.06	0.510
63.00	70.0	22.81	11.74	0.515
70.00	80.0	25.34	13.42	0.530
78.00	90.0	28.24	15.10	0.535

RUN NUMBER 120906 WATER CONTENT 50.4

FORCE	STRAIN	P1	P3	K
11.30	10.0	4.09	1.68	0.411
17.50	20.0	6.33	3.36	0.531
24.00	30.0	8.69	5.05	0.581
32.80	40.0	11.87	6.73	0.567
39.50	50.0	14.30	8.41	0.588
47.80	60.0	17.30	10.09	0.583
59.00	70.0	21.36	11.78	0.551
67.00	80.0	24.25	13.46	0.555
76.00	90.0	27.51	15.14	0.550

RUN NUMBER 120908 WATER CONTENT 57.6

FORCE	STRAIN	P1	P3	K
9.00	10.0	3.26	1.25	0.385
16.50	20.0	5.97	2.51	0.420
22.50	30.0	8.14	3.76	0.462
28.00	40.0	10.14	5.02	0.495
33.80	50.0	12.24	6.27	0.513
39.00	60.0	14.12	7.53	0.533
44.50	70.0	16.11	8.78	0.545
49.60	80.0	17.96	10.03	0.559
55.00	90.0	19.91	11.29	0.567
60.80	100.0	22.01	12.54	0.570
65.50	110.0	23.71	13.80	0.582
71.00	120.0	25.70	15.05	0.586

RUN NUMBER 120909 WATER CONTENT 57.6

FORCE	STRAIN	P1	P3	K
12.20	10.0	4.42	1.25	0.284
18.60	20.0	6.73	2.51	0.373
24.00	30.0	8.69	3.76	0.433
29.00	40.0	10.50	5.02	0.478
33.50	50.0	12.13	6.27	0.517
39.00	60.0	14.12	7.53	0.533
44.80	70.0	16.22	8.78	0.541
50.20	80.0	18.17	10.03	0.552
55.50	90.0	20.09	11.29	0.562
60.50	100.0	21.90	12.54	0.573
65.50	110.0	23.71	13.80	0.582
71.00	120.0	25.70	15.05	0.586

RUN NUMBER 121001 WATER CONTENT 61.0

FORCE	STRAIN	P1	P3	K
6.00	10.0	2.17	1.24	0.569
10.50	20.0	3.80	2.47	0.650
15.00	30.0	5.43	3.71	0.683
20.00	40.0	7.24	4.94	0.683
24.50	50.0	8.87	6.18	0.697
29.50	60.0	10.68	7.42	0.695
35.00	70.0	12.67	8.65	0.683
40.00	80.0	14.48	9.89	0.683
45.50	90.0	16.47	11.13	0.675
52.50	100.0	19.00	12.36	0.650
57.50	110.0	20.81	13.60	0.653
64.00	120.0	23.17	14.83	0.640

RUN NUMBER 121002 WATER CONTENT 61.0

FORCE	STRAIN	P1	P3	K
7.00	10.0	2.53	1.28	0.506
12.50	20.0	4.52	2.57	0.567
18.00	30.0	6.52	3.85	0.591
23.00	40.0	8.33	5.13	0.617
26.50	50.0	9.59	6.42	0.669
32.50	60.0	11.76	7.70	0.654
37.50	70.0	13.57	8.98	0.662
42,50	80.0	15.38	10.27	0.667
47.50	90.0	17.19	11.55	0.672
54.00	100.0	19.55	12.83	0.656
59.00	110.0	21.36	14.12	0.661
64.50	120.0	23.35	15.40	0.660
70.00	130.0	25.34	16.68	0.658
75.00	140.0	27.15	17.97	0.662
80.00	150.0	28.96	19.25	0.665

RUN NUMBER 121003 WATER CONTENT 61.0

FORCE	STRAIN	P1	P3	K
8.50	10.0	3.08	1.28	0.417
14.00	20.0	5.07	2.57	0.506
19.20	30.0	6.95	3.85	0.554
24.00	40.0	8.69	5.13	0.591
30.00	50.0	10.86	6.42	0.591
35.00	60.0	12.67	7.70	0.608
40.00	70.0	14.48	8.98	0.620
45.50	80.0	16.47	10.27	0.623
51.00	90.0	18.46	11.55	0.626
56.50	100.0	20.45	12.83	0.627
61.50	110.0	22.26	14.12	0.634
67.00	120.0	24.25	15.40	0.635
72.00	130.0	26.06	16.68	0.640
77.00	140.0	27.87	17.97	0.645
82.00	150.0	29.68	19.25	0.648

RUN NUMBER 121004 WATER CONTENT 61.0

FORCE	STRAIN	P1	P3	K
8.50	10.0	3.08	1.42	0.462
15.20	20.0	5.50	2.84	0.517
21.00	30.0	7.60	4.27	0.561
26.00	40.0	9.41	5.69	0.604
31.20	50.0	11.29	7.11	0.630
36.50	60.0	13.21	8.53	0.646
42.50	70.0	15.38	9.95	0.647
48.50	80.0	17.56	11.38	0.648
53.50	90.0	19.37	12.80	0.661
58.00	100.0	21.00	14.22	0.677
63.00	110.0	22.81	15.64	0.686
68.50	120.0	24.80	17.06	0.688

RUN NUMBER 121005 WATER CONTENT 59.3

FORCE	STRAIN	P1	P3	K
7.20	10.0	2.61	1.42	0.546
13.50	20.0	4.89	2.85	0.583
20.00	30.0	7.24	4.27	0.590
25.40	40.0	9.19	5.70	0.619
31.00	50.0	11.22	7.12	0.634
36.50	60.0	13.21	8.54	0.647
42.50	70.0	15.38	9.97	0.648
48.00	80.0	17.38	11.39	0.656
53.20	90.0	19.26	12.81	0.665
57.50	100.0	20.81	14.24	0.684
64.00	110.0	23.17	15.66	0.676
69.50	120.0	25.16	17.09	0.679
74.50	130.0	26.97	18.51	0.686
79.00	140.0	28.60	19.93	0.697

RUN NUMBER 121006 WATER CONTENT 59.3

FORCE	STRAIN	P1	P3	K
8.00	10.0	2.90	1.43	0.493
14.50	20.0	5.25	2.85	0.544
20.50	30.0	7.42	4.28	0.577
26.00	40.0	9.41	5.71	0.607
31.50	50.0	11.40	7.14	0.626
36.50	60.0	13.21	8.56	0.648
42.50	70.0	15.38	9.99	0.649
48.00	80.0	17.38	11.42	0.657
53.50	90.0	19.37	12.85	0.663
58.00	100.0	21.00	14.27	0.680
64.50	110.0	23.35	15.70	0.672
69.50	120.0	25.16	17.13	0.681
74.50	130.0	26.97	18.56	0.688
79.50	140.0	28.78	19.98	0.694

RUN NUMBER 121007 WATER CONTENT 59.3

FORCE	STRAIN	P1	P3	K
9.50	10.0	3.44	1.44	0.419
14.50	20.0	5.25	2.88	0.549
19.70	30.0	7.13	4.33	0.607
25.50	40.0	9.23	5.77	0.625
31.50	50.0	11.40	7.21	0.632
37.00	60.0	13.39	8.65	0.646
43.00	70.0	15.57	10.09	0.648
48.00	80.0	17.38	11.53	0.664
54.00	90.0	19.55	12.98	0.664
60.00	100.0	21.72	14.42	0.664
65.50	110.0	23.71	15.86	0.669
70.20	120.0	25.41	17.30	0.681

RUN NUMBER 121008 WATER CONTENT 59.3

FORCE	STRAIN	P1	P3	K
6.50	10.0	2.35	1.45	0.616
13.50	20.0	4.89	2.90	0.593
20.50	30.0	7.42	4.35	0.586
25.00	40.0	9.05	5.80	0.640
30.50	50.0	11.04	7.25	0.656
36.50	60.0	13.21	8.69	0.658
41.00	70.0	14.84	10.14	0.683
47.00	80.0	17.01	11.59	0.681
53.00	90.0	19.19	13.04	0.680
58.50	100.0	21.18	14.49	0.684
64.00	110.0	23.17	15.94	0.688

RUN NUMBER 121009 WATER CONTENT 59.3

FORCE	STRAIN	P1	P3	K
10.50	10.0	3.80	1.45	0.382
16.50	20.0	5.97	2.91	0.486
23.00	30.0	8.33	4.36	0.523
29.50	40.0	10.68	5.81	0.544
35.00	50.0	12.67	7.26	0.573
40.00	60.0	14.48	8.72	0.602
46.00	70.0	16.65	10.17	0.611
51.00	80.0	18.46	11.62	0.630
56.50	90.0	20.45	13.08	0.639
62.00	100.0	22.44	14.53	0.647
68.00	110.0	24.62	15.98	0.649

RUN NUMBER 121010 WATER CONTENT 57.1

FORCE	STRAIN	P1	P3	K
5.00	10.0	1.81	1.31	0.724
9.50	20.0	3.44	2.62	0.762
15.50	30.0	5.61	3.93	0.700
21.00	40.0	7.60	5.24	0.689
25.50	50.0	9.23	6.55	0.709
31.00	60.0	11.22	7.86	0.700
36.50	70.0	13.21	9.17	0.694
43.00	80.0	15.57	10.48	0.673
49.00	90.0	17.74	11.79	0.665
55.00	100.0	19.91	13.10	0.658
60.50	110.0	21.90	14.41	0.658
65.00	120.0	23.53	15.72	0.668

RUN NUMBER 121011 WATER CONTENT 57.0

FORCE	STRAIN	P1	P3	K
6.50	10.0	2.35	1.31	0.558
11.50	20.0	4.16	2.63	0.631
18.50	30.0	6.70	3.94	0.588
25.00	40.0	9.05	5.25	0.580
30.00	50.0	10.86	6.56	0.604
34.80	60.0	12.60	7.88	0.625
39.80	70.0	14.41	9.19	0.638
45.00	80.0	16.29	10.50	0.645
50.00	90.0	18.10	11.81	0.653
55.50	100.0	20.09	13.13	0.653
60.50	110.0	21.90	14.44	0.659

RUN NUMBER 121012 WATER CONTENT 57.0

FORCE	STRAIN	P1	P3	K
10.00	10.0	3.62	1.32	0.363
16.00	20.0	5.79	2.63	0.454
20.50	30.0	7.42	3.95	0.532
26.50	40.0	9.59	5.26	0.549
32.50	50.0	11.76	6.58	0.559
38.50	60.0	13.94	7.89	0.566
45.00	70.0	16.29	9.21	0.565
50.50	80.0	18.28	10.53	0.576
56.50	90.0	20.45	11.84	0.579
62.50	100.0	22.62	13.16	0.582

RUN NUMBER 121013 WATER CONTENT 67.0

FORCE	STRAIN	P1	P3	K
4.20	10.0	1.52	1.50	0.986
9.50	20.0	3.44	3.00	0.871
15.00	30.0	5.43	4.50	0.828
20.00	40.0	7.24	5.99	0.828
27.50	50.0	9.95	7.49	0.753
33.80	60.0	12.24	8.99	0.735
39.00	70.0	14.12	10.49	0.743
44.50	80.0	16.11	11.99	0.744
49.50	90.0	17.92	13.49	0.753
54.60	100.0	19.77	14.98	0.758
60.00	110.0	21.72	16.48	0.759
65.00	120.0	23.53	17.98	0.764
70.00	130.0	25.34	19.48	0.769
75.00	140.0	27.15	20.98	0.773

RUN NUMBER 121014 WATER CONTENT 67.0

FORCE	STRAIN	P1	P3	K
5.00	10.0	1.81	1.51	0.832
12.00	20.0	4.34	3.01	0.694
17.00	30.0	6.15	4.52	0.734
23.00	40.0	8.33	6.03	0.724
28.00	50.0	10.14	7.53	0.743
34.00	60.0	12.31	9.04	0.734
39.50	70.0	14.30	10.54	0.737
45.00	80.0	16.29	12.05	0.740
50.00	90.0	18.10	13.56	0.749
55.50	100.0	20.09	15.06	0.750
61.50	110.0	22.26	16.57	0.744

RUN NUMBER 10802 WATER CONTENT 62.3

FORCE	STRAIN	P1	P3	K
4.90	10.0	1.77	1.29	0.730
9.90	20.0	3.58	2.59	0.723
16.00	30.0	5.79	3.88	0.671
21.20	40.0	7.67	5.18	0.675
26.50	50.0	9.59	6.47	0.675
31.80	60.0	11.51	7.77	0.675
37.00	70.0	13.39	9.06	0.677
41.50	80.0	15.02	10.36	0.690
47.00	90.0	17.01	11.65	0.685
51.80	100.0	18.75	12.95	0.691

RUN NUMBER 11101 WATER CONTENT 68.0

FORCE	STRAIN	P1	P3	K
9.60	10.0	3.48	1.29	0.370
13.00	20.0	4.71	2.57	0.546
18.00	30.0	6.52	3.86	0.592
23.80	40.0	8.62	5.14	0.597
28.60	50.0	10.35	6.43	0.621
32.30	60.0	11.69	7.71	0.660
37.60	70.0	13.61	9.00	0.661
40.70	80.0	14.73	10.28	0.698
45.00	90.0	16.29	11.57	0.710
50.50	100.0	18.28	12.85	0.703

RUN NUMBER 11201 WATER CONTENT 71.3

FORCE	STRAIN	P1	P3	K
5.40	10.0	1.95	1.27	0.648
9.80	20.0	3.55	2.53	0.714
13.00	30.0	4.71	3.80	0.807
16.30	40.0	5.90	5.06	0.858
20.30	50.0	7.35	6.33	0.862
24.00	60.0	8.69	7.60	0.874
28.60	70.0	10.35	8.86	0.856
33.50	80.0	12.13	10.13	0.835
38.60	90.0	13.97	11.40	0.816
42.70	100.0	15.46	12.66	0.819

RUN NUMBER 11202 WATER CONTENT 58.1

FORCE	STRAIN	P1	P3	K
5.50	10.0	1.99	1.32	0.665
11.50	20.0	4.16	2.65	0.636
17.60	30.0	6.37	3.97	0.623
22.50	40.0	8.14	5.30	0.650
28.90	50.0	10.46	6.62	0.633
33.10	60.0	11.98	7.94	0.663
39.80	70.0	14.41	9.27	0.643
44.70	80.0	16.18	10.59	0.655
51.80	90.0	18.75	11.92	0.635

RUN NUMBER 11302 WATER CONTENT 66.3

FORCE	STRAIN	P1	P3	K
7.90	10.0	2.86	1.49	0.521
13.80	20.0	5.00	2.98	0.596
19.30	30.0	6.99	4.47	0.640
24.10	40.0	8.72	5.96	0.683
28.60	50.0	10.35	7.45	0.719
33.80	60.0	12.24	8.94	0.730
38.90	70.0	14.08	10.43	0.740
44.40	80.0	16.07	11.92	0.741
51.00	90.0	18.10	13.41	0.741
55.80	100.0	20.20	14.89	0.737

RUN NUMBER 11303 WATER CONTENT 61.1

FORCE	STRAIN	P1	P3	K
6.00	10.0	2.17	1.23	0.566
10.80	20.0	3.91	2.46	0.629
17.50	30.0	6.33	3.69	0.582
23.00	40.0	8.33	4.92	0.591
28.60	50.0	10.35	6.15	0.594
34.00	60.0	12.31	7.38	0.600
39.50	70.0	14.30	8.61	0.602
44.50	80.0	16.11	9.84	0.611
50.00	90.0	18.10	11.07	0.612
54.90	100.0	19.87	12.30	0.619

RUN NUMBER 11401 WATER CONTENT 55.4

FORCE	STRAIN	P1	P3	K
13.00	10.0	4.71	1.26	0.268
19.60	20.0	7.10	2.53	0.356
28.00	30.0	10.14	3.79	0.374
34.00	40.0	12.31	5.05	0.410
39.00	50.0	14.12	6.31	0.447
44.50	60.0	16.11	7.58	0.470
50.60	70.0	18.32	8.84	0.483
55.90	80.0	20.24	10.10	0.499
61.20	90.0	22.15	11.36	0.513
67.00	100.0	24.25	12.63	0.521
73.00	110.0	26.43	13.89	0.526
77.80	120.0	28.16	15.15	0.538

RUN NUMBER 11402 WATER CONTENT 59.7

FORCE	STRAIN	P1	P3	K
11.80	10.0	4.27	1.34	0.314
17.50	20.0	6.33	2.68	0.423
23.10	30.0	8.36	4.02	0.481
29.00	40.0	10.50	5.36	0.511
34.80	50.0	12.60	6.71	0.532
39.80	60.0	14.41	8.05	0.558
45.10	70.0	16.33	9.39	0.575
50.20	80.0	18.17	10.73	0.590
55.80	90.0	20.20	12.07	0.598
60.80	100.0	22.01	13.41	0.609
66.90	110.0	24.22	14.75	0.609
72.10	120.0	26.10	16.09	0.617

RUN NUMBER 11403 WATER CONTENT 55.8

FORCE	STRAIN	P1	P3	K
14.00	10.0	5.07	1.26	0.248
21.80	20.0	7.89	2.51	0.318
27.60	30.0	9.99	3.77	0.377
33.20	40.0	12.02	5.02	0.418
39.60	50.0	14.34	6.28	0.438
44.60	60.0	16.15	7.53	0.467
49.80	70.0	18.03	8.79	0.488
54.00	80.0	19.55	10.05	0.514

RUN NUMBER 11404 WATER CONTENT 54.0

FORCE	STRAIN	P1	P3	K
10.20	10.0	3.69	1.36	0.368
17.30	20.0	6.26	2.72	0.434
22.80	30.0	8.25	4.08	0.494
29.20	40.0	10.57	5.43	0.514
35.00	50.0	12.67	6.79	0.536
41.30	60.0	14.95	8.15	0.545
48.00	70.0	17.38	9.51	0.547
55.60	80.0	20.13	10.87	0.540
62.10	90.0	22.48	12.23	0.544
67.40	100.0	24.40	13.59	0.557

RUN NUMBER 11801 WATER CONTENT 53.8

FORCE	STRAIN	P1	P3	K
5.50	10.0	1.99	1.27	0.637
11.00	20.0	3.98	2.54	0.637
17.20	30.0	6.23	3.80	0.611
24.20	40.0	8.76	5.07	0.579
30.00	50.0	10.86	6.34	0.584
36.10	60.0	13.07	7.61	0.582
42.10	70.0	15.24	8.88	0.583
47.00	80.0	17.01	10.15	0.596
53.00	90.0	19.19	11.41	0.595
60.50	100.0	21.90	12.68	0.579
67.00	110.0	24.25	13.95	0.575
73.20	120.0	26.50	15.22	0.574

RUN NUMBER 11902 WATER CONTENT 63.9

FORCE	STRAIN	P1	P3	K
10.50	10.0	3.80	1.55	0.409
17.80	20.0	6.44	3.11	0.482
24.50	30.0	8.87	4.66	0.526
30.30	40.0	10.97	6.22	0.567
36.50	50.0	13.21	7.77	0.588
41.60	60.0	15.06	9.33	0.619
48.00	70.0	17.38	10.88	0.626
54.20	80.0	19.62	12.43	0.634
59.20	90.0	21.43	13.99	0.653
65.00	100.0	23.53	15.54	0.661
72.00	110.0	26.06	17.10	0.656
77.10	120.0	27.91	18.65	0.668
82.50	130.0	29.86	20.21	0.677

RUN NUMBER 11903 WATER CONTENT 52.9

FORCE	STRAIN	P1	P3	K
8.80	10.0	3.19	1.32	0.416
13.90	20.0	5.03	2.65	0.526
23.80	30.0	8.62	3.97	0.461
27.80	40.0	10.06	5.30	0.526
33.60	50.0	12.16	6.62	0.544
39.60	60.0	14.34	7.94	0.554
46.00	70.0	16.65	9.27	0.557
51.00	80.0	18.46	10.59	0.574
56.50	90.0	20.45	11.92	0.583
63.00	100.0	22.81	13.24	0.581
68.60	110.0	24.83	14.56	0.586
75.50	120.0	27.33	15.89	0.581
81.60	130.0	29.54	17.21	0.583
85.00	140.0	30.77	18.54	0.602

RUN NUMBER 11904 WATER CONTENT 51.6

FORCE	STRAIN	P1	P3	K
9.90	10.0	3.58	1.31	0.367
16.60	20.0	6.01	2.63	0.438
22.80	30.0	8.25	3.94	0.478
29.20	40.0	10.57	5.26	0.498
34.50	50.0	12.49	6.57	0.526
40.50	60.0	14.66	7.89	0.538
47.50	70.0	17.19	9.20	0.535
52.80	80.0	19.11	10.52	0.550
59.00	90.0	21.36	11.83	0.554
64.00	100.0	23.17	13.15	0.568
69.50	110.0	25.16	14.46	0.575
75.20	120.0	27.22	15.78	0.580
81.00	130.0	29.32	17.09	0.583
86.00	140.0	31.13	18.41	0.591

RUN NUMBER 12001 WATER CONTENT 45.4

FORCE	STRAIN	P1	P3	K
9.10	10.0	3.29	1.37	0.417
15.20	20.0	5.50	2.75	0.500
22.30	30.0	8.07	4.12	0.511
29.20	40.0	10.57	5.50	0.520
35.50	50.0	12.85	6.87	0.535
41.90	60.0	15.17	8.25	0.544
49.00	70.0	17.74	9.62	0.543
56.00	80.0	20.27	11.00	0.543
65.20	90.0	23.60	12.37	0.524
74.50	100.0	26.97	13.75	0.510

RUN NUMBER 12002 WATER CONTENT 63.5

FORCE	STRAIN	P1	P3	K
7.20	10.0	2.61	1.44	0.554
15.00	20.0	5.43	2.89	0.532
19.60	30.0	7.10	4.33	0.611
25.00	40.0	9.05	5.78	0.638
29.30	50.0	10.61	7.22	0.681
35.60	60.0	12.89	8.67	0.672
43.00	70.0	15.57	10.11	0.650
49.30	80.0	17.85	11.55	0.647
54.50	90.0	19.73	13.00	0.659
60.00	100.0	21.72	14.44	0.665
66.00	110.0	23.89	15.89	0.665
71.60	120.0	25.92	17.33	0.669
77.10	130.0	27.91	18.78	0.673

RUN NUMBER 12101 WATER CONTENT 44.0

FORCE	STRAIN	P1	P3	K
22.30	10.0	8.07	1.46	0.180
29.00	20.0	10.50	2.91	0.277
36.50	30.0	13.21	4.37	0.330
43.20	40.0	15.64	5.82	0.372
52.20	50.0	18.90	7.28	0.385
59.60	60.0	21.58	8.73	0.405
67.00	70.0	24.25	10.19	0.420
73.50	80.0	26.61	11.64	0.438
81.00	90.0	29.32	13.10	0.447
86.00	100.0	31.13	14.55	0.467

RUN NUMBER 12102 WATER CONTENT 6.1

FORCE	STRAIN	P1	P3	K
6.70	10.0	2.43	1.46	0.602
11.40	20.0	4.13	2.92	0.707
15.50	30.0	5.61	4.38	0.780
18.70	40.0	6.77	5.84	0.862
24.30	50.0	8.80	7.30	0.829
30.50	60.0	11.04	8.75	0.793
37.00	70.0	13.39	10.21	0.763
43.80	80.0	15.86	11.67	0.736
49.50	90.0	17.92	13.13	0.733
55.50	100.0	20.09	14.59	0.726
61.00	110.0	22.08	16.05	0.727
66.50	120.0	24.07	17.51	0.727
71.80	130.0	25.99	18.97	0.730
99.99	140.0	36.20	20.43	0.564

RUN NUMBER 12103 WATER CONTENT 62.0

FORCE	STRAIN	P1	P3	K
6.50	10.0	2.35	1.30	0.551
13.30	20.0	4.81	2.59	0.539
19.00	30.0	6.88	3.89	0.566
24.10	40.0	8.72	5.19	0.595
28.60	50.0	10.35	6.48	0.626
33.80	60.0	12.24	7.78	0.636
40.10	70.0	14.52	9.08	0.625
44.50	80.0	16.11	10.38	0.644
49.50	90.0	17.92	11.67	0.651
55.00	100.0	19.91	12.97	0.651
60.10	110.0	21.76	14.27	0.656
65.80	120.0	23.82	15.56	0.653
71.10	130.0	25.74	16.86	0.655
76.20	140.0	27.58	18.16	0.658
82.00	150.0	29.68	19.45	0.655

RUN NUMBER 12104 WATER CONTENT 44.6

FORCE	STRAIN	P1	P3	K
12.80	10.0	4.63	1.41	0.304
21.80	20.0	7.89	2.82	0.357
29.30	30.0	10.61	4.23	0.398
36.30	40.0	13.14	5.64	0.429
44.00	50.0	15.93	7.04	0.442
50.10	60.0	18.14	8.45	0.466
57.00	70.0	20.63	9.86	0.478
62.50	80.0	22.62	11.27	0.498

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13. ABSTRACT

The concepts associated with the field of soils mechanics are now being applied to marine sediments. Because of the more complex nature of the mixture of fine mineral particles and sea water, some of these concepts do not always appear overly applicable. This is particularly true with regard to the deep sea clays. In view of their often very high water contents, a liquid behavior might well be assumed for many marine clays. The analytical methods of fluid mechanics do not satisfactorily explain the low strengths that are found in these soils. Thin-walled test cylinders were devised to allow testing of cohesive soils at high water contents. Over 50 tests were made of a test sediment, the majority above the liquid limit, to study the relationship of plasticity to water content. The results show that the gradation from liquid to plastic behavior encompasses a much wider range of water contents than previously considered.

14 KEY WORDS	LINK A		LINK B		LINK C	
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Variation of Strength Characteristics with Water Content						
Liquid Limit						
Bi-state Behavior						

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